THE DISCOVERY OF 13 s X–RAY PULSATIONS FROM THE HYDROGEN DEPLETED SUBDWARF O6 STAR BINARY HD49798

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ABSTRACT

We discovered strong ~ 13 s X–ray pulsations in the Rosat PSPC light curve of HD49798, a 1.55 d single–component spectroscopic binary containing a hydrogen depleted subdwarf O6 star. We find no evidence for period changes during the ~ 4 hr Rosat pointing. The source X–ray spectrum is extremely soft, with an unabsorbed 0.1–2 keV luminosity of a few $\times 10^{32}$ erg s^{-1} (distance of 650 pc). A higher luminosity might be hidden in the EUV. Our results imply that the unseen companion is an accreting degenerate star, a white dwarf or, more likely, a neutron star. In either case HD49798 corresponds to a previously unobserved evolutionary stage of a massive binary system, after common envelope and spiral–in.

Subject headings: binaries: spectroscopic — pulsars: individual (HD49798) — stars: rotation — subdwarfs — X–ray: stars

1. Introduction

Subdwarf O stars form a fairly inhomogeneous group, spreading over a large range of temperatures, surface gravity and chemical compositions. Different evolutionary and nuclear histories probably contribute to the group of sdO stars, one of the late stages of stellar evolution that leads to the formation of white dwarfs (Bauer & Husfeld 1995).

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The case of HD49798 is especially intriguing because this 8th magnitude sdO6 star, is also a spectroscopic binary (with P_{orb} = 1.55 d, $a \sin i$ = 3.60 $R_{\odot}$, f(m) = 0.263 $M_{\odot}$; Thackeray 1970; Stickland & Lloyd 1994). Despite extensive studies, the nature of the companion star remained unclear for decades. Being very hot (T$\simeq$ 47000 K) and luminous (Log $(L/L_{\odot}) \simeq 3.90$) the sdO6 star outshines its companion (at least in the optical–UV). The level of H depletion, together with the underabundance of C the strong overabundance of N, testify that the outer layers were processed through the CNO cycle and the envelope of the progenitor star was lost during a common envelope phase. Kudritzki & Simon (1978) estimated a mass of $\sim 0.7 - 2.7$ $M_{\odot}$ for the sdO6 star and suggested a similar mass for the companion; they concluded that HD49798 resulted from non–conservative mass transfer. Bisscheroux et al. (1996) argued that the sdO star has a degenerate CO core and is in the phase of shell helium burning. Attempts at detecting the optical continuum of the companion provided conflicting conclusions: Thackeray (1970) and Kudritzki & Simon (1978) suggested a F4–K0 main sequence companion; Goy (1978) favored instead a compact star. We report here the discovery of 13 s pulsations in the soft X–ray flux from HD49798.

2. X–Ray Observations and Data Analysis

The field of HD49798 was observed on 1992 Nov 11 from 18:07 to 22:06 UT (exposure of 5453 s) with the Position Sensitive Proportional Counter (PSPC, 0.1–2.0 keV) in the focal plane of the X–ray telescope on board Rosat. Two X–ray sources were detected within $2'$ from the center of the Rosat pointing. The Rosat error circle of the brightest of the two sources (1WGA J0648.0–4418 center of RA = 06 48 04.6, DEC = –44 18 54.4 and radius of $\sim 10''$, equinox 2000) includes the optical position of HD49798 ($\sim 5''$ offset). The position of the $\sim$ $1.3'$ distant, weaker X–ray source 1WGA J0648.0–4419 (RA = 06 48 00.1, DEC = –44 19 30.5) is inconsistent with HD49798.

The Rosat light curve and spectrum of HD49798 contained $\sim$ 1000 photons extracted from a circle of $1'$ circle (containing to $>$ 95% of the PSF) around the X–ray position. The contamination from the background and 1WGA J0648.0–4419 amounts to $\sim$ 20 and $\sim$ 50 photons, respectively. In order to correct for both we used the photons extracted from a $1'$ circle centered $\sim 1.3'$ away from 1WGA J0648.0–4419 in the direction opposite to HD49798. By adopting different subtraction techniques we determined that only the PHA channels above $\sim$ 1 keV are somewhat affected.

The light curve of HD49798 was first analyzed as part of a study aimed at revealing periodicities in $\sim$ 23000 WGACAT X–ray sources (Israel & Stella 1996; Israel *et al.* 1996). The photon arrival times were corrected to the barycenter of the solar system and a 0.44 s binned light curve of HD49798 accumulated over the entire observation duration (3.7 hr). The corresponding power spectrum is shown in Fig. 1. The peaks around 0.0049 and 0.0125 Hz are seen in many Rosat sources and arise as a consequence of the wobble in the pointing direction (Israel *et al.* 1996). The 15σ peak at $\sim$ 0.076 Hz is instead unique to HD49798 The best period was determined to be 13.1789$\pm$0.0007 s by fitting the phases of the modulation

obtained over 6 different intervals of ~ 900 s exposure (all uncertainties are 90% confidence). The scatter of the phase residuals was consistent with a strictly periodic modulation at the best period (χ^2 of 4.7 for 4 degrees of freedom, dof). By adding a quadratic term to the fit a 3σ upper limit to the period derivative of $|\dot{P}| < 2.3 \times 10^{-7}$ s s^{-1} was derived. The folded light curve is shown as an insert in Fig. 1. The arrival time of the pulse minima (adopted as phase 0) was JD $2448938.332514 \pm 0.000007$. The large pulsed fraction ($\sim 60\%$) and nearly sinusoidal shape of the modulation are consistent with being energy–independent in the PSPC band. The 13 s X-ray pulsations prove that HD49798 hosts a degenerate star accreting from the sdO star wind (see Sect. 3).

The Rosat PSPC spectrum of HD49798 is extremely soft. Among single–component models, a power law produced by far the best fit (χ^2/dof of 22.1/14) for a photon index of $\Gamma = 4.7 \pm 0.5$ and an interstellar column density of $N_H = (2.1\pm^{0.7}_{0.4}) \times 10^{20}$ cm^{-2} (see Fig. 2a). The corresponding 0.1–2.0 keV X–ray flux at the earth is $F \sim 8\times10^{-13}$ erg cm^{-2} s^{-1}. For the estimated distance of 650 pc (Kudritzki & Simon 1978) this converts to an unabsorbed luminosity of $\sim 4\times10^{32}$ erg s^{-1}. The extrapolation of this spectrum towards low energies provides a flux about two orders of magnitude lower than the IUE flux measurement at 1200Å ($\sim 2 \times 10^{-10}$ erg cm^{-2} s^{-1} Å^{-1}, Bohlin *et al.* 1990). This indicates that a luminosity of up to $\sim 10^{34} - 10^{35}$ erg s^{-1} might be hidden in the EUV.

Fig. 2a shows that a large contribution to the χ^2 derives from a deficit of photons in the 0.4-0.6 keV range. Given the temperature, flux and peculiar composition of the sdO star atmosphere, HeII and the higher ionization stages of N (from NIV up) should dominate the wind optical depth for photon energies in the PSPC band (see Sect. 3). This leads to a natural interpretation of the 0.4-0.6 keV deficit in terms of K-edge absorption from N ions in the wind. By including an edge at 0.46 keV (NIV) the power law fit provides a χ^2/dof of 10.0/13, for an optical depth of $\tau_N = 3.4\pm^{3.0}_{1.9}$. This gives an F–test probability of 1.5×10^{-3} for the addition of one free parameter. In this case Γ is 4.1 ± 0.4, while N_H remains unchanged. Similar results are obtained if a NV K-edge at 0.50 keV is used. An upper limit to the HeII absorption in the wind can be obtained by ascribing the entire low energy absorption to these ions, *i.e.* setting the interstellar absorption N_H to zero; this gives $\tau_{HeII} < 120$ for an edge at 54 eV, with 90% confidence. As discussed in Sect. 3, the N and He optical depths obtained above would be reconciled if most of the He in the sdO star wind were fully ionized. Note that with the inclusion of an N-edge at 0.46 keV, a blackbody model provides also a reasonably good fit ($\chi^2/dof = 17.8/13$) for a temperature of $kT_{bb} = 114 \pm 12$ eV and equivalent radius of $R_{bb} = 2.2\pm^{0.4}_{0.6}$ km; this gives a bolometric blackbody luminosity of $0.7 - 2 \times 10^{32}$ erg s^{-1}.

The Rosat PSPC spectrum of HD49798 can also be interpreted in terms of the sum of a black body spectrum plus a high energy excess, described by a power law (Israel et al. 1995). The lower $\chi^2/dof = 9.7/13$ resulting from the addition of two free parameters to the power law model gives an F–test probability of 7×10^{-3}. The best fit is obtained for $kT_{bb} \simeq 18.4$ eV, $\Gamma \simeq 3$ and $N_H \simeq 5 \times 10^{20}$ cm^{-2} (see Fig. 2c). The contribution of the high energy power law component is $\sim 30\%$. In this interpretation the spectral paramaters are poorly constrained. This is clearly seen from Fig. 2d where confidence contours are plotted in the $N_H - kT_{bb}$ plane.

Only a lower limit of $N_H > 10^{20}$ cm^{-2} and an upper limit of $kT_{bb} < 50$ eV can be deduced from the Rosat spectrum. A very wide range of black body luminosities is allowed, starting from 2×10^{32} erg s^{-1} (see Fig. 2d). This is due to the fact that, for decreasing temperatures, a larger and larger fraction of the black body flux would be hidden in the EUV.

The 1400 s *Einstein* HRI (0.05–4.0 keV) observation of HD49798 of 1979 March 19 revealed an insufficient number of photons (~ 40) to confirm the 13 s period. To within the uncertainties the Einstein HRI count rate is consistent with the Rosat PSPC measurements.

The EXOSAT CMA (0.05–2 keV) observed HD49798 on 1983 September 21 for a total of ~7400 s. The source was observed at a count rate of 0.63 ± 0.04, 0.40 ± 0.03 and 0.035 ± 0.005 cts s^{-1}, respectively with the polypropilene (PPL), 3000Å and 4000Å Lexan filters. The ratio of these rates is incompatible with any plausible X-ray spectrum, clearly indicating a high level of UV contamination in the CMA data. The marginally significant ~ 14.4 s periodicity that we found in the PPL light curve is almost certainly introduced in the event processing by the on board computer (similar to other CMA sources).

According to the ephemeris of Stickland & Lloyd (1994), the Rosat and *Einstein* observations took place at orbital phase $0.00 - 0.10$ and $0.80 - 0.82$, respectively. Therefore the presence of an X-ray eclipse (expected to be centered at 0.75) cannot be ruled out yet.

3. Discussion

The discovery of 13 s pulsations in the X–ray flux of HD49798 proves that the long–sought companion is a degenerate star, either a white dwarf or a neutron star. The inferred radius of the sdO star is $R_* \sim 10^{11}$ cm, about a half of its Roche Lobe. Therefore, mass transfer towards the companion must be driven by the sdO star wind. Based on the the P–Cygni profile of the NV resonance doublet, Hamann *et al.* (1981) determined that the terminal wind velocity of $v_w \sim 1350$ km s^{-1} is reached at $\sim 1.7\ R_*$, *i.e.* within the Roche Lobe of the sdO star. The estimated mass loss rate $\dot{M}_*$ ranges between 5×10^{-10} and 10^{-8} M$_\odot$ yr^{-1}. Bisscheroux et al. (1996) argue that $\dot{M}_*$ can be as high as $\sim 3 \times 10^{-8}$ M$_\odot$ yr^{-1} and the bulk of the wind matter (mainly H and He) as slow as $v_w \sim 800$ km s^{-1} By using the whole range of estimated v_w and $\dot{M}_*$, and the standard theory of wind accretion in binary systems (see White, Nagase & Parmar 1995 and references therein) we derive a mass capture rate of $\dot{M}_x \sim 10^{11} - 6 \times 10^{14}$ g s^{-1} by the degenerate companion. In deriving these values we used an orbital velocity of the degenerate star in the $80 - 160$ km s^{-1} range, as obtained from the measured mass function and velocity amplitude ($K \simeq 118$ km s^{-1}) by allowing the degenerate and sdO star mass to be $0.85 - 1.5$ M$_\odot$ and $0.7 - 2.1$ M$_\odot$, respectively. (Note that the upper limit of 2.1 M$_\odot$ is obtained from the mass function by using $i = 90^{\rm o}$ and a maximum mass of 1.5 M$_\odot$ for the degenerate star). For the adopted mass range the system inclination is $i \geq 46^{\rm o}$.

By using $\dot{M}_x$ given above, an accretion luminosity of $2 \times 10^{28} - 2 \times 10^{32}$ erg s^{-1} is predicted in the case of a white dwarf and of $1 \times 10^{31} - 1 \times 10^{35}$ erg s^{-1} in the case of a neutron star. While the former range is only marginally consistent with the inferred unabsorbed luminosity

in the PSPC band (see Sect. 2), the second overlaps comfortably, allowing also for a larger luminosity in the EUV. By using the maximum angular momentum of the accretion flow relative to the companion, a circularization radius of $\leq 10^7$ cm is derived. This excludes the presence of an accretion disk in the case of a white dwarf. A disk could form outside a neutron star magnetosphere only for magnetic fields of $B \leq 3 \times 10^8 (\dot{M}_x/10^{15}\text{g s}^{-1})^{1/2}$ G.

The galactic HI column in the direction of HD49798 is $\sim 6 \times 10^{20}$ cm^{-2} (Stark *et al.* 1992). Uncertainties are introduced by the $\sim 2^o$ radio beam-averaging. Moreover a fraction of the column might be beyond HD49798, despite its height above the galactic plane (~ 210 pc). We conclude that the estimate above is not in contradiction with the range of $\sim 1 - 3 \times 10^{20}$ cm^{-2} derived from the PSPC spectrum.

At the descending node (close to the phase of the Rosat observation), the expected column density from a spherical wind is $N_{H,w} \simeq 5 \times 10^{20} (\dot{M}_*/10^{-8}\text{M}_\odot\ \text{yr}^{-1})(v_w/10^3\text{km s}^{-1})^{-1}(a/5 \times 10^{11}\text{cm})^{-1}$ cm^{-2}, with a the orbital separation. Abundances in the sdO star atmosphere are published only for He ($\times 2.8$ solar), C ($\times 0.05$), N ($\times 25$) and Si ($\times 1.4$) (cf. Bauer & Husfeld 1995). The absence of substantial O, Ne and Mg lines indicates that these elements are underabundant (probably $\times 0.1 - 0.3$, similar to other sdO stars). Therefore in the Rosat PSPC energy range, He and N should dominate the photoelectric absorption by the wind (H is virtually 100% ionized); indeed given the UV flux from the sdO star the most populated stages are probably HeII and NIV-NVI. In the following we discuss the X-ray spectrum of HD49798 in the relation to the expected absorption properties of the wind.

In the white dwarf interpretation, the required mass inflow rate implies that the wind optical depth at the HeII and NIV–VI edges is ≥ 2000 and ≥ 4, respectively. Therefore for the upper limit on the HeII optical depth not to be violated (see Sect. 2), the fraction of HeIII must be very large. The white dwarf accretion luminosity is insufficient to photoionize HeII. The required level of He ionization could be due to an additional wind heating mechanism (temperatures $\geq 10^5$ K), such as, possibly, the friction between a low and a high speed wind component (see Springmann & Pauldrach 1992). In any case, a conspicuous N K-edge should be present around energies of $0.46 - 0.55$ keV (ionization stages above He-like N would not be populated). This, in turn, favors the spectral decomposition involving a power law and a N K-edge (see Sect. 2).

If the accreting object is a neutron star, the observed 0.1-2 keV luminosity can be produced for smaller mass inflow rates which do not require appreciable wind absorption from HeII and NIV–VI. Accretion luminosities of up to $\sim 10^{35}$ erg s^{-1}, as suggested by the extrapolation of the steep power law–like PSPC spectrum to the EUV, would still be compatible with the wind parameters. In this case the EUV luminosity could photoionize He to the required level, while a NIV–VI K–edge optical depth of a few could still be present. For bolometric luminosities in the $10^{32} - 10^{35}$ erg s^{-1} range, the blackbody plus power law model implies $R_{bb} \sim 20 - 2000$ km (see Fig. 2d) a difficult range to reconcile with a neutron star.

3.1. White Dwarf accretor

If the degenerate star in HD49798 is a white dwarf, it would be the first example of a white dwarf accreting from an early type (though very unusual !) companion. The 13 s X–ray pulsations might originate from magnetic polar cap accretion, as in the case of intermediate polars (IPs). The 13 s rotation period would then be the shortest known. By requiring that the magnetospheric radius is smaller than the corotation radius ($r_m < r_c$), such that the "centrifugal barrier" is open and accretion can take place, we derive $B \leq 5 \times 10^3 (\dot{M}_x / 10^{15} \mathrm{g\ s}^{-1})^{1/2}$ G. This value is substantially lower than the range inferred for IPs ($\sim 10^5 - 10^7$ G). While most IPs display hard X–ray spectra, a small subgroup with spin periods of 5–15 min is characterized by an additional very soft spectral component, which probably originates from the reprocessing at the white dwarf surface of the primary hard X–ray radiation emitted at the end of the accretion column(s) (Duck *et al.* 1994; Haberl & Motch 1995). The very soft X-ray spectrum of HD49798, however, must have a different origin. Indeed in this case, $r_c \sim 8 \times 10^8$ cm sets an upper limit of ~ 3 white dwarf radii, r_{wd}, to r_m. Accretion is therefore expected to take place over a large fraction of the white dwarf surface, $f \sim r_{wd}/r_m \sim 1/3$ (see e.g. Frank, King & Raine 1985). This is far larger than the R_{bb} derived from blackbody fits for luminosities of $\sim 10^{32}$erg s^{-1} (see Sect. 2 and Fig. 2d).

The nova-like variable AE Aqr presents a composite soft X–ray spectrum with a luminosity of $\sim 10^{31}$ erg s^{-1} and X–ray pulsations at the 33 s white dwarf spin period, currently the fastest known (Eracleous *et al.* 1991). The power implied by the measured spin-down rate far exceeds the UV and X–ray luminosity (de Jager *et al.* 1994). This, together with the absence of an accretion disk, indicates that AE Aqr hosts a magnetic white dwarf in the "propeller" regime, which expels most of the inflowing matter, causing large spin-down torques (Wynn, King & Horne 1996). It is unlikely that HD49798 hosts a similar propeller, as this would require a wind mass capture rate $\gg 10^{15}$ g s^{-1}.

The limit on the coherence Q of the ~ 13 s signal in the Rosat light curve of HD49798 ($Q \geq 10^6$) suggests an analogy with the $\sim 10 - 30$ s quasi–coherent oscillations ($Q \sim 10^4 - 10^6$), that are seen at soft X–ray and EUV energies during the outbursts of dwarf novae, such as SS Cyg and U Gem (Córdova *et al.* 1980; Jones & Watson 1992; Mauche 1996). Note that the outburst X-ray spectra of these system are very soft ($kT_{bb} \sim 25 - 30$ eV). The origin of these oscillations is still debated, but they are known to be associated to disk-accreting cataclysmic variables accreting at rates of $\sim 10^{15}$ g s^{-1}. White dwarf disk accretion, however, is ruled out for HD49798.

3.2. Neutron Star accretor

If HD49798 hosts an accreting magnetic neutron star, then the ~ 13 s pulsations arise from its rotation. The higher energy conversion efficiency makes it easier to reconcile the mass capture rate inferred from the sdO star wind properties not only with the measured luminosity in the Rosat PSPC band, but also with plausible extrapolations to the EUV. We note that in

the single blackbody (plus N edge) interpretation of the PSPC spectrum, the inferred black body radius is consistent with a neutron star. The condition that the centrifugal barrier is open requires $B \leq 6 \times 10^{11}(\dot{M}_x/10^{15}\text{g s}^{-1})^{1/2}$ G. An accretion disk cannot form unless B is three orders of magnitude lower. HD49798 should therefore alternate spin–up and spin–down episodes, similar to those observed in wind-fed X–ray pulsars (cf. White *et al.* 1995). The spectra of most X-ray pulsars are hard ($\Gamma \sim 0 - 2$) and extend to energies of several tens of keV. However a group of 4-5 accreting pulsars with 5-9 s periods and very soft X-ray spectra ($\Gamma \sim 2 - 5$) has been recently identified (Mereghetti & Stella 1995). This group is also characterized by X-ray luminosities of $\sim 10^{35} - 10^{36}$ erg s^{-1} and secular spin-down, indicating that the neutron stars are close to their equilibrium period and have a relatively low B of $\sim 10^{11.5} - 10^{12}$ G. Clearly there are similarities with the case of HD49798. On the other hand these X-ray pulsars either have a very low mass companion, or are isolated and accrete from a residual disk (van Paradijs *et al.* 1995).

In this interpretation, HD49798 would be the first X–ray binary with an early type H-depleted mass donor. Such system would likely be the remnant of a high mass X–ray binary after common envelope and spiral in, an evolutionary phase that has not been seen before. If the sdO star is too light to undergo gravitational collapse, the system will evolve in $\sim 10^6$ yr into a non-interacting binary consisting of a massive white dwarf and a neutron star. Even if mass transfer rate were maintained throughout this transition at its current maximum value, the neutron star could be spun-up only if $B \leq 3 \times 10^8$ G, achieving a minimum period of ~ 7 $(B/10^8 \text{ G})^{6/7}$ ms (i.e. the "spin–up line" for $\dot{M}_x \sim 10^{15}$ g s^{-1}). The currently known millisecond pulsars with massive white dwarf companions have substantially shorter spin periods (Bailes *et al.* 1994; Camilo *et al.* 1996): therefore a system like HD49798 could not be their progenitor.

4. Conclusions

Our results prove that HD49798 hosts either a white dwarf or, more likely, a magnetic neutron star. The value and sign of any changes in the ~ 13 s X-ray period should clarify the nature of the accreting degenerate star. The dwarf nova oscillation scenario requires quasi–coherent oscillations. If instead the ~ 13 s pulsations arise directly from the rotation of the degenerate star, they would be coherent enough to make HD49798 a "double spectroscopic" binary; in this case the system would hold a great potential for accurate mass measurements of a previously unobserved evolutionary stage.

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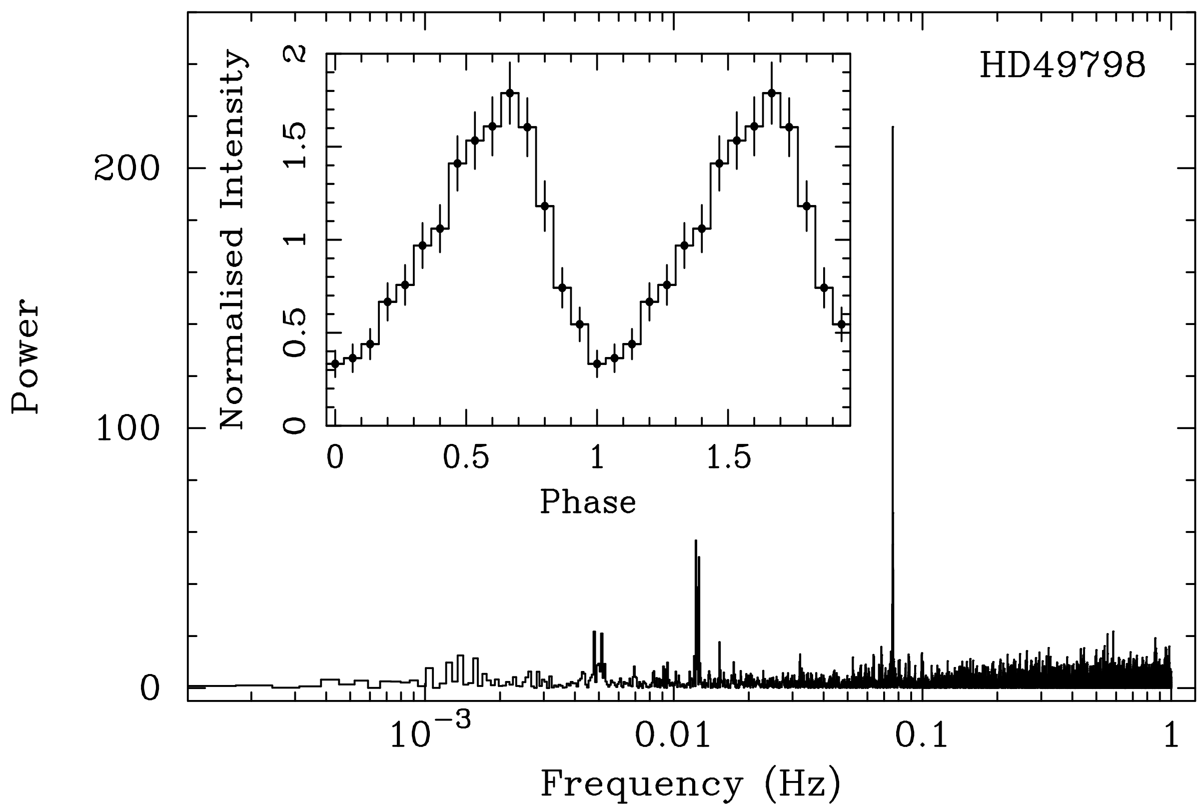
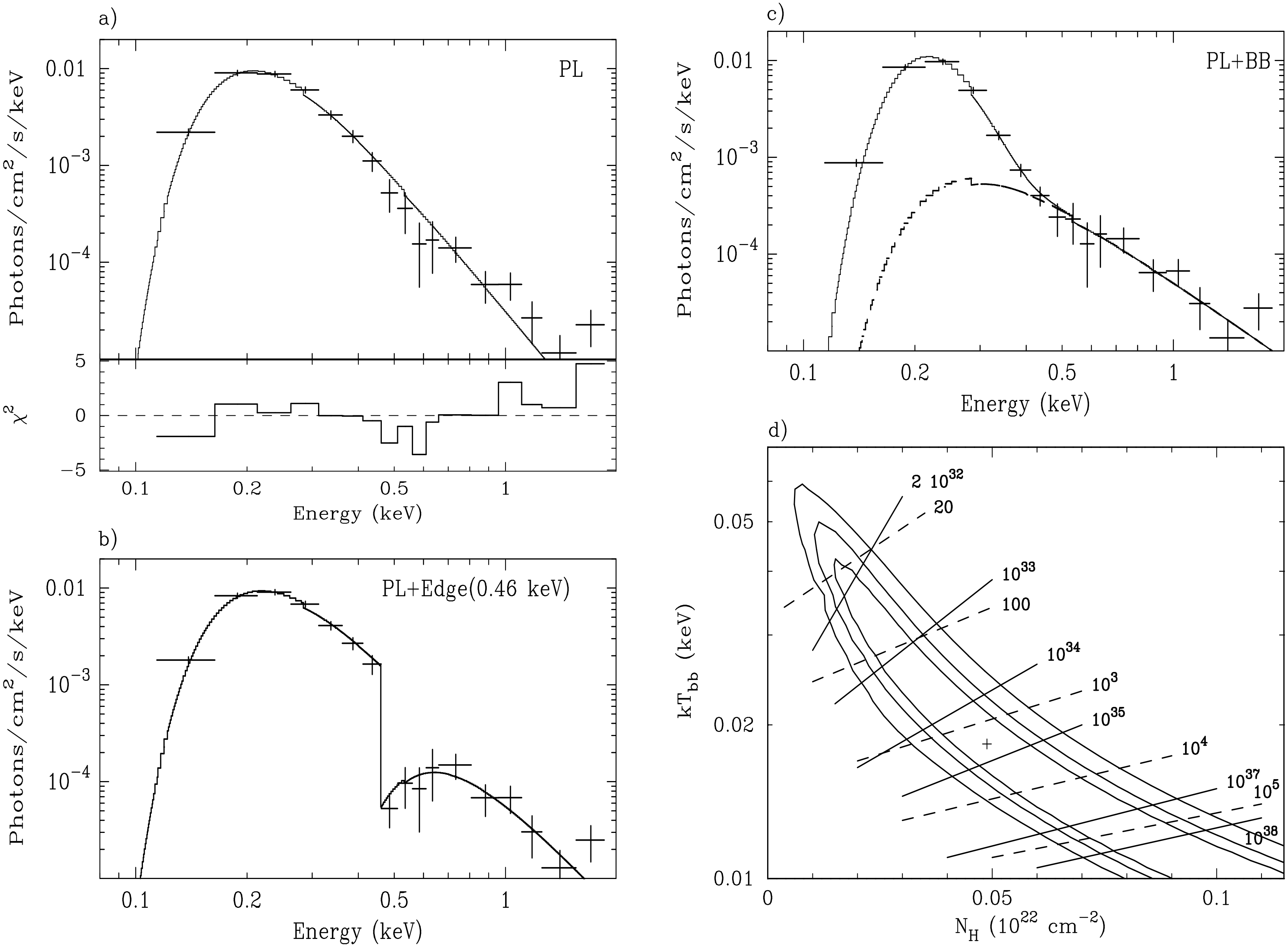
Figure Captions

Figure 1: Power spectrum of the 0.1–2.0 keV ROSAT PSPC light curve of HD49798. The highest peak, centered around 0.076 Hz, corresponds to the 13.2 s pulsations. The folded lightcurve is shown in the inner panel.

Figure 2: Unfolded spectra and best fit models from the ROSAT PSPC observation of HD49798. Panel *a* refers to the power law model (residuals are also shown), panel *b* to the power law and NIV K-edge model and panel *c* to the blackbody plus power law model. Panel d shows the the 68.3% , 95.4% and 99.7% confidence level contour plot in the $N_H - kT_{bb}$ plane for the model in panel c. Lines of constant black body radius R (in km, dashed lines) and bolometric luminosity L_{bb} (in erg s^{-1}, solid lines) are also shown.



HD49798
Power
Frequency (Hz)
Normalised Intensity
Phase



a)
PL
Photons/cm²/s/keV
χ²
Energy (keV)
b)
PL+Edge(0.46 keV)
Photons/cm²/s/keV
Energy (keV)
c)
PL+BB
Photons/cm²/s/keV
Energy (keV)
d)
kT_bb (keV)
N_H (10^22 cm^-2)
2 10^32
20
10^33
100
10^34
10^3
10^35
10^4
10^37
10^5
10^38